Resonances, and mechanisms of Θ-production

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After explaining necessity of exotic hadrons, we discuss mechanisms which could determine production of the exotic Θ-baryon. A possible important role of resonances (producing the Θ in real or virtual decays) is emphasized for various processes. Several experimental directions for studies of such resonances, and the Θ itself, are suggested. We briefly discuss also recent negative results on the Θ-baryon.

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The problem of multiquark (exotic and/or "cryptoexotic") states is as old as quarks themselves. The first experimental results on searches for exotics [1, 2, 3] were published soon after invention of quarks [4, 5]. Initial straightforward motivation "Why not?" was later supported by duality considerations [6] (the duality was understood at those times as correspondence between the sum over resonances and the sum over reggeons). However, several years of experimental uncertainty generated the question: "Why are there no strongly bound exotic states ..., like those of two quarks and two antiquarks or four quarks and one antiquark?" [7].

An attempt to give a reasonable, though model-dependent, answer to this question was made in the confined relativistic quark model (so called MIT bag) [8, 9, 10]. Its main conclusion was that the multiquark states should exist, and so "... either these states will be found by experimentalists or our confined, quark-gluon theory of hadrons is as yet lacking in some fundamental, dynamical ingredient which will forbid the existence of these states or elevate them to much higher masses" [8].

What is very essential, neither of approaches based on QCD could change this statement, which, therefore, has become even stronger with time going. However, details of expected properties of exotic hadrons are rather different in different approaches. For instance, the MIT bag prescribes $J^P = 1/2^-$ for the lightest baryon with $S = +1$ [9], while the chiral soliton approach (ChSA) predicts $J^P = 1/2^+$ (see Refs. [11, 12] for recent reanalyses of ChSA predictions and more detailed references). Mass of such a baryon should be either about 1700 MeV, in MIT bag [9], or, in ChSA, most probably below 1600 MeV [13]. Predicted widths of exotic hadrons strongly differ as well. MIT bag explains unsuccessful searches for exotic states by their too broad widths, of several hundreds MeV [8, 9, 10], while, according to ChSA, at least some exotic states may be quite narrow as compared to familiar resonances [14]. Numerous more recent theoretical papers use various theoretical approaches, and yet could not resolve ambiguities for expected properties of the exotic hadrons.

Long-time absence of definite experimental results on exotics had practically stopped the corresponding activity, and Reviews of Particle Properties ceased to touch the exotics problem after the issue of 1986 [15]. Nevertheless, the paper of Diakonov, Petrov, and Polyakov [14], that predicted the lightest exotic baryon to have mass about 1530 MeV and width less than 15 MeV, strongly stimulated new experimental attempts. They provided, at last, positive evidence for the baryon Θ^+ with $S = +1$. Its observation has been stated now in more than 10 publications [16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26], and the measured mass about 1540 MeV looks similar to expectations of the ChSA.

However, spin and parity of Θ are unknown yet, its in-

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directly estimated width of order 1 MeV [27, 28, 29, 30] seems to be unexpectedly narrow even for ChSA. Moreover, each of the existing positive experiments on Θ has relatively low statistics (mainly about 40-50 events above background) which looks insufficient today. Therefore, even existence of the Θ^+ still needs more indisputable proof.

Meanwhile, there have appeared some experimental publications which do not see the Θ^+ [31, 32, 33]. Really, they do not contradict its existence. Indeed, restrictions of Ref. [31] are rather weak (see Appendix, for their more detailed discussion), and some features of data of Ref. [32] still hint for possibility to extract Θ^+. Ref. [33] gives the most bright illustration of the present uncertain status: the Conference talk with "a statistically significant peak" of $\overline{\Theta}^-$ has transformed into the Proceedings contribution with "no structure" statement. That is why we will not discuss here other evidences for the Θ-non-observation, still being at the level of rumors and/or slides (a long list of them is given, *e.g.*, in Ref. [34]). Nevertheless, we like to note that searches for Θ^+ even now use very different processes, with different initial particles and different energies. Amplitudes and cross sections of these processes may (and should) contain contributions of various quite different mechanisms, and not all of them produce the Θ. Therefore, some procedures to separate the mechanisms may be inevitable, before one can observe the Θ^+, even if it has been produced.

We wish to emphasize, however, that if the present evidences for Θ appeared incorrect, it would not make the situation easier, since all the old "damned" questions on exotics would immediately revive. Therefore, we take today more conservative position, that Θ does exist, but its production in different conditions is governed by different mechanisms, with very different intensity. Though we essentially agree with suggestions of Karliner and Lipkin [34] how to clarify the problem, we think that, first of all, it is especially important to reliably confirm existence of Θ in the processes where it has been stated to be seen. The corresponding new data are being collected and treated just now by several collaborations.

In the present note, we discuss qualitative features of possible mechanisms of the Θ-production and suggest some lines of investigations to clarify them.

Even the first information on Θ^+ initiated attempts to understand how it is produced, and estimate the production cross section. If, for definiteness, we consider the photoproduction processes

$$\gamma + n \to K^- + \Theta^+ \tag{1}$$

and/or

$$\gamma + p \to \overline{K}^0 + \Theta^+ \tag{2}$$

(and related electroproduction processes, with virtual photons), then the most evident contributions come from exchanges by strange mesons (K and K^*, first of all) in the t-channel, and by baryons (Θ and its possible excitations) in the u-channel. There are also s-channel contributions which correspond, first of all, to formation of various resonances with non-exotic quantum numbers.

All those exchange contributions decrease with increasing energy. To understand this, consider, for example, exchanges by mesons, K and/or K^*. At high energies, they should be reggeized, and their contributions to the amplitudes are $\sim s^{\alpha_i(t)}$, where $\alpha_i(t)$ is the reggeon trajectory, with $i = K$ and/or K^*. Being integrated over scattering angles, such contributions reveal energy behavior $\sim s^{2\alpha_i(0)-1}$. Known Regge trajectories may be taken, with good accuracy, to be linear,

$$\alpha(t) \approx \alpha(0) + \alpha' t\,,$$

with $\alpha' \approx 1$ GeV^{-2}. Then, for K and K^* exchanges, having $\alpha_K(m_K^2) = 0$ and $\alpha_{K^*}(m_{K^*}^2) = 1$, we obtain $2\alpha_K(0) - 1 \approx -1.5$ and $2\alpha_{K^*}(0) - 1 \approx -0.6$. Therefore, contributions of the both meson exchanges, and their interference as well, decrease at high energies. Note, that the K^* exchange vanishes somewhat slower (and, therefore, becomes more essential) at high energies, than the K exchange. Similar conclusions may be obtained for baryon exchanges, and also for exchange contributions in other reactions of Θ-production.

Thus, exchanges can not determine the Θ-production at high energies, though might be essential at some moderate energies. To check such possibility, we can compare the Θ photoproduction processes to strangeness photoproduction with usual, non-exotic hadrons in the final state. Take, for example, reactions

$$\gamma + N \to K + \Lambda(\Sigma)\,. \tag{3}$$

They are kinematically similar to reactions (1) and (2), and have the same t-channel exchanges. These processes have been studied experimentally by different collaborations [35]. Analyses of the data, up to photon energies E_γ of several GeV, suggest that important contributions come not only from exchanges, but also from various s-channel resonances. Similar conclusions seem to be true as well for photoproduction of mesons η [36] and η' (see Ref. [37] and references therein), which contain $s\overline{s}$ pairs.

By analogy, we expect that the Θ-photoproduction should also be essentially determined by contributions of some resonances. What could be those resonances? Up to now, we know only one such candidate, evidenced for by the CLAS Collaboration at JLab [22] and corresponding to a rather narrow peak in the mass distribution of the system $(K^-\Theta^+)$ near 2400 MeV. We will call it $N^*(2400)$.

Note, however, that the measured spectrum [22] may suggest evidence for some other peaks as well. Moreover, just as in the cases of photoproduction of kaon-hyperon or η, and especially for η'-photoproduction, the resonances contributing to the Θ-photoproduction do not need to be real; they can be virtual, subthreshold or overthreshold. So, even some well-known, rather light nucleon resonances could participate in reactions (1) and (2), even though, because of low mass, they can decay to $\overline{K}\Theta$ only virtually.

Resonances may be essential also for the inclusive Θ-production at high energies. For example, $N^*(2400)$ (or some its analog) might be produced in diffraction dissociation of the initial nucleon, and then decay to Θ^+. The corresponding cross section could be non-decreasing (or slowly decreasing) with energy growing. This does not mean that the cross section would be large. Just opposite, it will inevitably contain a smallness. If the resonance is mainly 3-quark system, its branching to Θ^+ should be small (we consider the smallness of the coupling between the Θ and KN channel as a general phenomenon). If the resonance is mainly multi-quark, its branching to Θ may be large, but its diffraction production should be suppressed. Thus, the Θ-production at high energies can be nonvanishing, but may be essentially determined by other mechanisms, and appear smaller, as compared to intermediate energies.

Here we would like to note Ref. [38] which mainly reviews results of the SPHINX Collaboration. Its Figs. 5, 11, and 14a show small, but rather clear bump in the spectrum of the diffraction excitation

$$p \to \Sigma^0 K^+ \,,$$

having just $M = 2400$ MeV. The same bump seems to be seen at Fig. 12 for the excitation

$$p \to \Sigma^+ K^0 \,,$$

and at Fig. 14b for

$$p \to p\,\eta \,.$$

It could be one more independent manifestation of $N^*(2400)$. If so, its smallness could be a confirmation of its (mainly) multi-quark structure.

Since the $N^*(2400)$ is today the only hypothetical resonance directly related to Θ^+, let us discuss its properties in some more detail. Isospin of $N^*(2400)$ should be $I = 1/2$, to allow the decay into $\overline{K}\Theta$, with Θ being isosinglet. Further, the state $N^*(2400)$ was discovered [22] in the reaction

$$\gamma + p \to \pi^+ + K^- + \Theta^+ \,, \quad \Theta^+ \to K^+ + n \,, \tag{4}$$

being seen as an intermediate stage of the cascade

$$\gamma + p \to \pi^+ + n^*(2400) \,, \quad n^*(2400) \to K^- + \Theta^+ \,. \tag{5}$$

The kinematical cuts were applied so to enhance contribution of the pion exchange. Therefore, $N^*(2400)$ emerges here as a resonance in the process

$$\pi^- + p \to K^- + \Theta^+ \,, \tag{6}$$

with the virtual initial pion. This means that $N^*(2400)$ needs to have nonvanishing coupling to the πN-channel. It should, thus, have the corresponding decay mode, and appear as a resonance in the πN interaction. Of course, such a heavy πN resonance may have sufficiently small elastic branching ratio, capable to make it practically unobservable in the elastic πN scattering. In any case, no partial wave analysis of πN scattering data in this mass range has seen $N^*(2400)$ with the total width of more or about 100 MeV and elasticity of more or about 5% [39].

In this connection, it would be very interesting to study the reaction (6) with the real negative pion. We expect that the process should reveal a rather narrow enhancement at about $T_\pi = 2.45$ GeV. Such investigations would be very interesting for studies of both Θ^+ and πN-resonances.

Let us discuss possible $SU(3)_F$ properties of $N^*(2400)$. As explained, it should be coupled to both πN channel (where each particle belongs to the corresponding flavor octet), and $\overline{K}\Theta$ (one octet and one antidecuplet hadrons). Since (see, *e.g.*, Ref. [40])

$$8\times 8 = 1+8_F+8_D+10+\overline{10}+27, \quad 8\times\overline{10} = 8+\overline{10}+27+\overline{35}\,, \tag{7}$$

then, in the case of the exact $SU(3)_F$ symmetry, $N^*(2400)$ should belong to one of the three flavor multiplets: 8, $\overline{10}$, or 27 (of course, the antidecuplet here is not that which contains Θ^+).

Studies of $N^*(2400)$, formed in photoproduction (1) and/or (2) as the s-channel resonance at $E_\gamma \approx 2.6$ GeV, could help to discriminate these cases. To explain this point, we may use the notion of U-spin [41]. It is analogous to the I-spin, that is, to the familiar isospin. But if the I-spin mixes u- and d-quarks, with s-quark being singlet, then the U-spin mixes d- and s-quarks, having the same electric charge, with u-quark being singlet. Therefore, all members of any U-spin multiplet should have the same electric charge. This implies, that if $SU(3)_F$ is exact and the photon interaction with quarks is universal, up to electric charges, the photon is the U-spin singlet, and its absorption can not change U-spin of an initial hadron.

Now, let us compare "protons" and "neutrons" in different unitary multiplets. The p-like component of every octet (together with Σ^+) belongs to a U-spin doublet, having $U = 1/2$. On the other side, the n-like component of the same octet (together with Ξ^0 and a combination of Σ^0 and Λ^0 components) is a member of a U-spin triplet, and has $U = 1$. For an antidecuplet, the n-like component also has $U = 1$ (together with Σ^0 and Ξ^0), while the p-like component has $U = 3/2$ (together with Θ^+, Σ^+, and Ξ^+). Situation for a 27-plet is more complicated: the p-like component (with $I = 1/2$) is a superposition of two parts, with $U = 1/2$ and $3/2$, while the n-like component (also with $I = 1/2$) consists of parts with $U = 1$ and 2 (compare to the photon, being the U-spin singlet, but having isoscalar and isovector parts).

Note, that the initial hadrons in the reaction (6) have $U(\pi^-) = U(p) = 1/2$, and their total U-spin can be either 0 or 1. On the other side, the final hadrons have $U(K^-) = 1/2$, $U(\Theta^+) = 3/2$, and their admissible U-spin is 1 or 2. Thus, only U-vector part of $n^*(2400)$ could contribute to this reaction, if $SU(3)_F$ were exact (even if $n^*(2400)$ is the member of a 27-plet).

Now, if we compare photoexcitation of $n^*(2400)$ and $p^*(2400)$, correspondingly, on the usual n and p, their relation depends on $SU(3)_F$-properties of $N^*(2400)$. In particular, if $N^*(2400)$ belongs to an antidecuplet, then photoexcitation of $p^*(2400)$ is forbidden, for exact $SU(3)_F$.

Of course, $SU(3)_F$ is violated. And nevertheless, one can reasonably expect that the photoexcitation of $N^*(2400)$, being the member of $\overline{10}$, goes much more intensively on the neutron than on the proton. As an example, we can remind similar consideration [42] for photoexcitation of the nonstrange partner of Θ^+ on the neutron and proton with accounting for $SU(3)_F$-violation.

Interesting information on the nature of $N^*(2400)$ could come from its excitation (observed through decay to Θ^+) in electroproduction, *i.e.* in reactions (1) and (2) with the virtual photon. If the $N^*(2400)$ is mainly 5-quark state, then its coupling to the mainly 3-quark nucleon should be small at vanishing photon virtuality Q^2. However, as we know from DIS-studies, the role of multiquark configurations inside the nucleon becomes more important at increasing Q^2. This may provide growing of the effective $\gamma^* N N^*(2400)$-coupling, when Q^2 rises from zero. Correspondingly, the electroexcitation of $N^*(2400)$ may increase with Q^2, at least, in some interval from zero.

There is one more way to study the electromagnetic vertex $\gamma^* N N^*(2400)$. It is to search for the annihilation

$$e^+ e^- \to \overline{N}\, N^*(2400) + \text{c.c.}\,. \tag{8}$$

This could be done inclusively, by missing mass to the nucleon. Similar search for N^*, with subsequent decay $N^* \to N\pi$, was recently published by BES Collaboration [43], but specifically in the peak of J/ψ, where only masses below 2160 MeV are kinematically allowed. The state $N^*(2400)$ could be produced in decays of $\psi(2S)$, but with a different, non-electromagnetic vertex. It would provide, therefore, different information than the reaction (8) in continuum.

Another possibility is to study the exclusive form of the process (8),

$$e^+ e^- \to p\, K_S\, \overline{n}\, K^- + \text{c.c.}\,, \tag{9}$$

accounting for the consequent decays

$$N^*(2400) \to \Theta^+ \overline{K}, \quad \Theta^+ \to NK\,.$$

The final state (9) has also been studied by BES [31], but only in peaks J/ψ and $\psi(2S)$, where the leading contribution is non-electromagnetic, while the vertex $\gamma^* N N^*(2400)$ appears to be a small correction. It could be essential for e^+e^--annihilation in continuum, but the present statistics there is small.

In summary, we have reminded necessity, at the present level of understanding strong interactions, of exotic hadrons, and discussed various mechanisms of Θ-production. We have emphasized, in such processes, a special possible role of resonances as intermediate objects. Production of Θ in very different processes, *e.g.*, photo- and electroproduction, e^+e^--annihilation, diffraction excitation, and others, may be useful to study both the Θ itself, and the related resonances.

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APPENDIX A: Θ^+ IN DECAYS OF CHARMONIUM

Collaboration BES investigated decays

$$J/\psi,\, \psi(2S) \to p\, K_S\, \overline{n}\, K^- + \text{c.c.} \tag{A1}$$

to search for single and/or double production of Θ^+. According to their publication [31], Θ (or $\overline{\Theta}$) was not found at the level of 10^{-5}. Let us discuss this in more detail.

The boundary obtained for the double Θ-production from the J/ψ is

$$\text{Br}(J/\psi \to \Theta\overline{\Theta} \to K_S p K^- \overline{n} + K_S \overline{p} K^+ n) < 1.1 \cdot 10^{-5}\,, \tag{A2}$$

while in the $\psi(2S)$-decays

$$\text{Br}(\psi(2S) \to \Theta\overline{\Theta} \to K_S p K^- \overline{n} + K_S \overline{p} K^+ n) < 0.84 \cdot 10^{-5}\,. \tag{A3}$$

These boundaries can not be directly compared to other known results. However, using the branching ratios

$$\text{Br}(\Theta \to K^+ n) = 1/2\,, \quad \text{Br}(\Theta \to K_S p) = 1/4\,,$$

one can derive

$$\text{Br}(J/\psi \to \Theta\overline{\Theta}) < 0.44 \cdot 10^{-4}\,, \tag{A4}$$

$$\text{Br}(\psi(2S) \to \Theta\overline{\Theta}) < 0.34 \cdot 10^{-4}\,, \tag{A5}$$

and compare them to other measured branchings. For instance [44],

$$\text{Br}(J/\psi \to \Lambda\overline{\Lambda}) = (13.0 \pm 1.2) \cdot 10^{-4}\,.$$

At first sight, the pair $\Theta\overline{\Theta}$ in J/ψ-decays is strongly suppressed in comparison with $\Lambda\overline{\Lambda}$, at least, by the factor < 0.034. But really, essential part of this suppression, 0.15, comes from kinematics (S-wave decay near threshold: c.m. kinetic energy $M_{J/\psi} - 2M_\Theta \approx 17$ MeV). The dynamical suppression factor is much weaker, < 0.23. For decays of $\psi(2S)$, similar comparison with [44]

$$\text{Br}(\psi(2S) \to \Lambda\overline{\Lambda}) = (1.81 \pm 0.34) \cdot 10^{-4}$$

gives even weaker suppression, < 0.19, with the kinematical factor 0.69 and the dynamical suppression < 0.27 (compare it to the dynamical factor < 0.23 above).

The most stringent restrictions for single Θ-production are

$$\text{Br}(J/\psi \to K_S p\, \overline{\Theta} \to K_S p K^- \overline{n}) < 1.1 \cdot 10^{-5} \tag{A6}$$

for J/ψ decays, and

$$\text{Br}(\psi(2S) \to K_S p\, \overline{\Theta} \to K_S p K^- \overline{n}) < 0.60 \cdot 10^{-5} \tag{A7}$$

for $\psi(2S)$. Again, one should use branchings to obtain

$$\text{Br}(J/\psi \to K^0 p\, \overline{\Theta}) < 0.44 \cdot 10^{-4}\,, \tag{A8}$$

$$\text{Br}(\psi(2S) \to K^0 p\, \overline{\Theta}) < 0.24 \cdot 10^{-4}\,. \tag{A9}$$

The first of these boundaries may be compared to [44]

$$\text{Br}(J/\psi \to K^- p\, \overline{\Lambda}) = (8.9 \pm 1.6) \cdot 10^{-4}\,, \tag{A10}$$

with the suppression factor < 0.049. An only appropriate reference value for decays of $\psi(2S)$ might be [44]

$$\text{Br}(\psi(2S) \to \pi^0 p\, \overline{p}) = (1.4 \pm 0.5) \cdot 10^{-4}\,, \tag{A11}$$

which provides the suppression factor < 0.029. We see that the total suppression for the single Θ-production in decays of J/ψ and $\psi(2S)$ is nearly the same as for the double Θ-production in decays of J/ψ (recall the factor of 0.034). It is difficult to separate here kinematical and dynamical factors, but one can expect somewhat stronger kinematical suppression in single Θ-decays, because of 3-body phase space.

Thus, data of BES [31] require some suppression in charmonium decays producing one or two Θ-baryon(s). However, they still admit rather soft dynamical suppression, say, 1/5 in the probability. Meanwhile, because of necessity to produce directly two more quark-antiquark pairs (in exotic decays as compared with decays to canonical baryon-antibaryon pairs), some dynamical suppression should naturally arise. It could be even stronger than the achieved boundaries. Thus, the recent result of BES [31] is only a starting point for investigating exotics in e^+e^--annihilation.

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